

Large scale measurements of soil moisture for validation of remotely sensed data: Georgia soil moisture experiment of 2003[☆]

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Received 2 November 2004; revised 11 August 2005; accepted 18 August 2005

Abstract

A series of soil moisture experiments were conducted in 2003 (SMEX03) to develop enhanced datasets necessary to improve spatiotemporal characterization of soil moisture and to enhance satellite-based retrievals. One component of this research was conducted in South Central Georgia of the US, from June 17th to July 21st (SMEX03 GA). This study analyzes measurements of soil moisture and temperature collected during SMEX03 GA. A network of in situ soil moisture measurement devices, established to provide validation data for the satellite collections and for long-term estimation of soil moisture conditions throughout the region, provided continuous measurements at 19 sites. Additional soil moisture and temperature validation data were collected daily from 49 field sites. These sites represented a diversity of land covers including forest, cotton, peanut, and pasture. Precipitation that occurred prior to June 22nd and from June 29th through July 2nd produced drying conditions from June 23rd to June 28th and gradual wetting from June 29th through July 2nd. Soil moisture in the top 0–1 cm of the soil was found to be more responsive to precipitation and to have greater variability than soil moisture at the 0–3 or 3–6 cm layers. Within different land covers, soil moisture followed the same trends, but varied with land use. Pasture sites were consistently the wettest while row-crop sites were normally the driest. Good agreement was observed between soil moisture measurements collected with the in situ network and the 49 SMEX sites. For the study period, soil moisture across the entire 50 km by 75 km region and five of the six 25 km by 25 km EASE-Grids demonstrated time stable characteristics. Time stability analysis and statistical tests demonstrated the in situ stations had a small dry bias as compared to the SMEX03 GA measurements. These

[☆] Contribution from the USDA-ARS, Southeast Watershed Research Laboratory, P.O. Box 748, Tifton, GA 31793, in cooperation with Univ. of Georgia Coastal Plain Exp. Station. All programs and services of the U.S. Department of Agriculture are offered on a nondiscriminatory basis without regard to race, color, national origin, religion, sex, age, marital status, or handicap.

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results indicate that the in situ network will be a good resource for long-term calibration of remotely sensed soil moisture and provide a new and unique source for future satellite product validation.

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Keywords: Soil moisture; Remote sensing; Spatial variability

1. Introduction

Because of its dominant influence on key physical processes, knowledge of soil moisture is important in many disciplinary and crosscutting scientific applications (e.g. ecology, biogeochemical cycles, climate monitoring, flood forecasting). Soil moisture characterizations have several applications: examination of the effect of climate change on land surface hydrological variables—infiltration fluxes, runoff, and surface temperature; characterization of feedback effects on soil moisture and surface temperature caused by changes in heat fluxes; characterization of changes in the simulated and observed planetary boundary layer depths due to variations in the surface temperature, soil moisture, and heat fluxes; quantification of the amount and variability of regional water resources on seasonal and annual time scales; and examination of the impact of assimilation of the derived land surface variables on predictive capabilities of meso-scale and global circulation models.

Accurate and reliable soil moisture estimates have important implications for continuing research in the studies of land-atmosphere interactions. There is strong climatological and modeling evidence that the fast recycling of water through evapotranspiration and precipitation is the primary factor in the persistence of dry or wet anomalies over large continental regions during summer. Because of this, soil moisture is the most significant boundary condition that controls summer precipitation over the central US and other large mid-latitude continental regions, and essential initial information for seasonal predictions. A common goal of a wide range of agencies and scientists is the development of a global soil moisture observing system (Leese et al., 2001). This system will provide global estimates of soil moisture utilizing in situ data, remotely sensed data, and model output. Koster et al. (1999) illustrate the enhanced predictability resulting from the correct knowledge of soil moisture fields.

Precise in situ measurements of soil moisture are sparse and each value is only representative of a small area. Remote sensing, if achievable with sufficient accuracy and reliability, can provide truly meaningful wide-area soil moisture data for hydrological studies over large continental regions. Passive microwave sensing (radiometry) has been shown to have some advantages as the remote-sensing method for predicting soil moisture (Jackson and O'Neill, 1987, 1990; Laymon et al., 2001). Measurements are directly sensitive to changes in surface soil moisture, are little affected by clouds and have been shown to penetrate moderate amounts of vegetation.

In an attempt to collect these global estimates of soil moisture, the National Aeronautics and Space Administration (NASA) launched the Advanced Microwave Scanning Radiometer for the Earth Observation System (AMSR-E) instrument aboard the Aqua satellite in May of 2002. AMSR-E is a 12-channel, six-frequency, passive microwave radiometer system. It measures brightness temperatures at 6.925, 10.65, 18.7, 23.8, 36.5, and 89.0 GHz, vertically and horizontally polarized. Along with estimates of soil moisture, AMSR-E yields estimates of precipitation, cloud water, water vapor, sea surface winds, sea surface temperature, and ice and snow cover. A second AMSR instrument was launched aboard the Midori II (also called ADEOS II) satellite by the Japan Aerospace Exploration Agency (JAXA) in December of 2002.

These instruments were projected to provide accurate estimates of soil moisture over the entire world. Data from the instruments are the first attempt at routinely mapping surface soil moisture. However, proper calibration and testing of the data are necessary to fully develop their usefulness. Soil moisture products from the instruments have to be validated because the retrieval algorithms utilize formulations, parameters, and ancillary data that are not thoroughly developed and verified.

For wider application of the AMSR-E soil moisture products and estimates from other passive microwave instruments, the data must be evaluated for a diverse geographic coverage, particularly for areas with heavier vegetation cover. As part of this testing, a series of soil moisture experiments (SMEX) have been carried out throughout the World to relate the remotely sensed measurements to ground based observations. One of the components of SMEX was a large-scale ground-based experiment conducted in south-central Georgia, USA, in June and July of 2003 (SMEX03 GA). A network of in situ soil moisture measurement devices was established to provide validation data for the satellite collections and for long-term estimation of soil moisture conditions throughout the region. During the field campaign, additional soil moisture and temperature data were collected from field sites for the network verification and calibration.

This manuscript provides an overview of the SMEX03 GA experiment and a detailed description and analysis of the soil-based moisture and temperature measurements that accompanied the study. An examination of the utility of the in situ network for future applications is also presented. The objectives of this research were to (1) collect ground based soil moisture data within a heavily vegetated coastal plain region which could be used to test retrievals based on data collected by AMSR-E and other satellite and aircraft based instruments, (2) examine the spatial and temporal variability of the soil moisture data and compare to climatic, soil, and land-use characteristics, and (3) validate the utility of the in situ soil moisture network using time stability analysis.

2. Methods

2.1. Project overview

The study was conducted during June and July of 2003. The area selected for the Georgia component of SMEX03 lies within the coastal plain region of the Southeastern United States (Fig. 1). Coordinates for the coverage area extended from latitude 31.19° N (UTM 3453508 m) to 31.88° N (UTM 3530926 m) and from longitude 83.41°W (UTM 270400 m) to 83.97°W (UTM 219086 m). The region covered

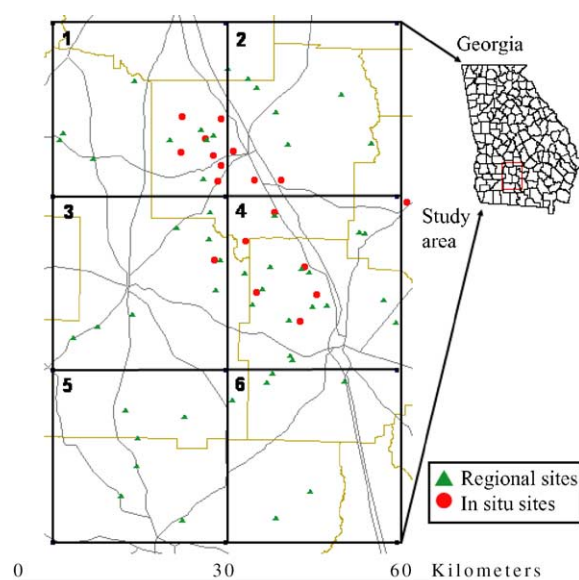


Fig. 1. SMEX03 GA regional sampling sites, in situ soil moisture sites, and EASE-grid cells.

a 50 km by 75 km area which was further divided into six 25 km by 25 km equal-area scalable earth grid (EASE-Grid) boxes (Brodzik and Knowles, 2002) (Table 1). The study region included the 334 km² Little River Experimental Watershed (LREW) in the headwaters of the Suwannee River Basin (Sheridan, 1997). Precipitation and stream flow data have been collected from the LREW since 1968 when the USDA-ARS Southeast Watershed Research Laboratory first began conducting research there. The area

Table 1

EASE-grid points for the grid vertices over the study region

UTM northing ^a (m)	UTM easting (m)
3530926	221138
3505462	220448
3480054	219764
3454714	219086
3530285	245770
3504824	245141
3479419	244517
3454082	243899
3529704	270400
3504246	269832
3478843	269269
3453508	268710

^a Coordinates are listed in the Universal Transverse Mercator (UTM) coordinate system Zone 17 NAD83 horizontal datum.

experiences long, hot, humid summers, and short, mild winters. The average annual precipitation is approximately 1200 mm. Precipitation during the summer months typically occurs in short duration high intensity thunderstorms with relatively small spatial extent (Bosch et al., 1999).

The study region contains broad flood plains with very poorly defined stream channels and gently sloping uplands. The topography is relatively flat, with upland slopes varying from 1 to 5%. The region is heavily vegetated. Approximately 36% of the region is forested, 40% cropland, 18% pasture, and the remaining area is wetlands and residential. Major crops are peanuts and cotton. Swamp hardwoods occur along the stream edges and are often accompanied by thick vegetation. The dominant soil type is a sandy loam. Most of the soils in the study area are well drained and have a sandy surface layer and a heavier textured subsoil. In general, the soils have fairly low water holding capacities. Field capacities of surface horizons range from 10 to 30% (Hubbard et al., 1985).

Climatic, vegetation, and soil-based measurements were collected within the coverage area to support the effort. Vegetation data were collected from June 17th to July 21st, 2003. Soil moisture and temperature data were collected primarily during the period from June 23rd to July 2nd, 2003. The ground based soil moisture sampling was conducted to coincide with satellite and scheduled aircraft overpasses. Fifty-two sample sites were selected for soil and vegetation sampling and for collection of eddy-flux evapotranspiration data (Table 2). Forty-nine of these sites were selected for soil moisture and soil temperature sampling (referred to as the regional sampling sites). Daily measurements were collected from these regional sites. Twelve sites out of the 52 were selected for vegetation sampling and three for eddy-flux measurements.

A network of 35 tipping bucket precipitation gages within the LREW recorded 5-min cumulative rainfall. In addition, there is one Soil Climate Analysis Network (SCAN) site (<http://www.wcc.nrcs.usda.gov/scan/>) and four meteorological stations maintained by the University of Georgia (Table 3). Measurements collected at the climate stations include air temperature, barometric pressure, wind speed, precipitation, relative humidity, solar radiation,

soil temperature, and soil moisture. One Eddy flux site was established in each of the three dominant non-forested vegetation types, pasture, peanuts, and cotton. Measurements of cumulative precipitation were made for each 24 h period between site visits at the regional sampling sites, roughly corresponding to a period from 11 to 11 a.m. EST.

To provide the necessary estimates of vegetation cover and vegetation water content, several measurements were collected in a diversity of land covers during the period from June 17, 2003 to July 21, 2003 (Table 2). The general purpose of the vegetation sampling was to characterize water storage within the plant canopy. Samples were collected four times throughout the study period at each of the 12 vegetation sites. Samples were collected once at each site every 7 days from June 17 to July 1 and then again 14 days later. In addition to the vegetation samples collected to estimate green and dry biomass, measurements of plant height, plant density, percentage ground cover, phenology, surface roughness, and leaf area index were made at each site. The vegetation samples were collected to capture various growth stages of the primary crops. One complete sampling of all of the vegetation sites took 2–3 days.

2.2. Remotely sensed data

Data from the study were collected primarily to support the testing of soil moisture retrievals based upon data from the AMSR-E and AMSR instruments aboard the Aqua and Midori-II satellites. However, data collected from other remotely sensed platforms, satellite and aircraft, are also being assembled for comparison to the ground based measurements. The polarimetric scanning radiometer (PSR) (Piepmeier and Gasiewski, 2001), the two-dimensional synthetic aperture radiometer (2DSTAR) (Le Vine et al., 1990, 1994), and the Global Positioning System (GPS) Bistatic Radar (Armatys et al., 2000; Masters et al., 2000, 2001) instruments were used to collect measurements over the study area on June 25th, 29th, and 30th, 2003. The instruments were flown on the NASA P3-B aircraft. A GPS system was also operated from a Cessna 206 flown at low altitude over the study region. The goals of the aircraft measurements were to collect data for both algorithm development/verification and soil moisture mapping.

Table 2
Location of the regional and vegetation sampling sites

Site name	Crop type	Station type ^a	Irrigated	UTM northing (m)	UTM easting (m)	Sand (%)	Silt (%)	Clay (%)
GA01	Peanuts	Soil	No	3513939	243680	91	6	3
GA02	Forest	Soil	No	3513374	242703	86	11	3
GA03	Peanuts	Soil	No	3514750	242062	84	9	7
GA04	Forest	Soil	No	3513393	237624	78	16	6
GA05	Strip-till cotton	Soil	No	3522195	232719	85	12	3
GA06	Pasture	Soil	No	3510933	226318	77	17	5
GA07	Peanuts	Soil	No	3513922	221691	85	11	4
GA08	Forest	Soil	No	3514845	222305	74	21	5
GA09	Young pines	Soil	No	3507716	242207	75	22	4
GA10	Pasture	Soil	No	3523615	246002	81	17	3
GA11	Corn	Soil	Yes	3522153	248964	83	12	5
GA12	Strip-till cotton	Soil	No	3520822	250147	88	8	4
GA13	Pasture	Soil	No	3517199	252810	89	10	1
GA14	Forest	Soil	No	3519483	262206	90	7	3
GA15	Strip-till cotton	Soil	Yes	3512203	266321	80	14	5
GA16	Forest	Soil	No	3512414	254429	86	11	3
GA17	Cotton	Soil	No	3484801	222888	78	12	10
GA18	Cotton	Soil	No	3486329	226415	81	11	7
GA19	Forest	Soil	No	3488126	231540	92	7	2
GA20	Strip-till cotton	Soil/vegetation	Yes	3500566	238201	87	9	4
GA21	Cotton	Soil	No	3502698	242956	90	8	2
GA22	Forest	Soil	No	3498881	242773	91	7	2
GA23	Double row peanuts	Soil/vegetation	Yes	3495686	244280	83	11	6
GA24	Pasture	Soil	No	3491302	243544	88	11	1
GA25	Forest	Soil	No	3480753	254340	70	21	8
GA26	Cotton	Soil	Yes	3481509	254049	84	9	7
GA27	Pasture	Soil/vegetation	No	3486713	253896	84	13	3
GA28	Peanuts	Soil	Yes	3489124	248693	86	11	3
GA29	Forest	Soil/vegetation	No	3491249	250318	76	20	4
GA30	Pasture	Soil	No	3494580	251449	86	10	4
GA31	Peanuts	Soil/vegetation	Yes	3493726	247830	79	12	9
GA32	Forest	Soil	No	3499136	265144	90	7	3
GA33	Cotton	Soil/vegetation	Yes	3499266	264355	85	11	4
GA34	Cotton	Soil/vegetation	Yes	3501976	252240	89	7	3
GA35	Peanuts	Soil	No	3494103	255847	84	10	6
GA36	Double row peanuts	Soil/vegetation	Yes	3493653	256946	83	7	10
GA37	Cotton	Soil	Yes	3488527	257233	86	10	3
GA38	Cotton	Soil	Yes	3457604	237835	76	11	13
GA39	Forest	Soil	No	3461586	229151	90	8	2
GA40	Pasture	Soil	No	3465867	231527	83	8	9
GA41	Peanuts	Soil	Yes	3469928	231776	84	10	5
GA42	Peanuts	Soil	Yes	3474069	230141	91	6	3
GA43	Forest	Soil	No	3472875	238551	77	19	5
GA44	Pasture	Soil	No	3478866	251353	75	19	6
GA45	Strip till cotton	Soil/vegetation	Yes	3477639	250494	87	10	3
GA46	Forest	Soil	No	3475165	245550	88	9	3
GA47	Cotton	Soil	Yes	3457563	251445	86	12	3
GA48	Cucumbers	Soil	Yes	3461506	256464	76	8	16
GA49	Forest	Soil/vegetation	No	3477481	261842	88	9	3
GA50	Pasture	Vegetation/eddy flux	No	3488702	259440	87	11	2
GA51	Double row peanuts	Vegetation/eddy flux	No	3489345	267584	89	9	2
GA52	Cotton	Eddy flux	No	3486042	269327	87	12	1

^a Sites sampled during regional soil moisture sampling vegetation sampling and eddy flux measurements.

Table 3
Locations of the in situ soil moisture and climate stations

Site name	UTM northing coordinate (m)	UTM easting coordinate (m)	Elevation (m)	Soil type
RG08	3486396	255514	90	Ocilla loamy sand 0–5% slope
RG12	3490633	249416	101	Fuquay loamy sand 0–5% slope
RG16	3494245	256307	123	Tifton loamy sand 2–5% slope
RG22	3498174	248094	105	Tifton loamy sand 2–5% slope
RG26	3502329	252215	116	Tifton loamy sand 2–5% slope
RG31	3507136	244193	122	Tifton loamy sand 2–5% slope
RG32	3507197	249514	123	Tifton loamy sand 2–5% slope
RG34	3509417	244772	112	Fuquay loamy sand 0–5% slope
RG37	3511512	239007	133	Tifton loamy sand 2–5% slope
RG39	3510911	243605	113	Fuquay loamy sand 0–5% slope
RG40	3511504	246611	134	Tifton loamy sand 2–5% slope
RG43	3513275	242616	132	Tifton loamy sand 2–5% slope
RG50	3516117	244911	113	Sunsweet gravelly sandy loam 5–12% slope
RG52	3516720	239359	141	Fuquay loamy sand 0–5% slope
RG63	3490205	258057	111	Fuquay loamy sand 0–5% slope
RG65	3503419	271327	95	Troup sand 0–5% slope
RG66	3507013	253304	91	Tifton loamy sand 2–5% slope
RG67	3495586	243409	95	Tifton loamy sand 2–5% slope
RG68	3477727	275188	88	Tifton loamy sand 2–5% slope
NRCS SCAN	3488532	256395	107	Dothan loamy sand 2–5% slope
UGA CPES	3487796	259420	116	Tifton loamy sand 0–2% slope
UGA Lang	3489682	258246	112	Tifton loamy sand 0–2% slope
UGA Ponder	3489066	248474	119	Tifton loamy sand 0–2% slope
UGA Gibbs	3480417	254291	105	Tifton loamy sand 0–2% slope

2.3. Ground based measurements

Daily ground based measurements of soil moisture and temperature were made from June 23rd to July 2nd, 2003. The goal of the regional sampling was to provide a reliable estimate of the mean and the variance of the volumetric soil moisture and soil temperature within a single satellite passive microwave footprint (~50 km by 50 km) and within multiple EASE-grid (25 km by 25 km) cells at the nominal time of the Aqua overpass (1:30 p.m. EST). To accomplish this, all of the regional sampling was conducted during a period within approximately 90 min of the overpass. The first sample was collected at approximately 11:30 a.m. EST and the final sample was collected around 2:30 p.m. EST.

The 49 regional sites were selected to cover a diversity of land covers and to provide approximately

six sites within each EASE-Grid cell with a nominal spacing of 8–10 km between sites (Table 4). A slightly greater site density was selected within the LREW in order to coincide with the instrumentation network available there. The site identification, land-use, and coordinates for each sampling location are shown in Table 2.

The daily measurements at each site were soil moisture in the top 0–6 cm of the profile and soil temperature in the top 10 cm. One set of soil moisture measurements from the top 0–6 cm of the profile were made with Theta capacitance probes (Dynamax Inc., ML2X Theta Probe)⁵. Theta probes measure a dielectric constant for the soil and converts this to volumetric soil moisture based upon a factory provided calibration equation (Gaskin and Miller, 1996). Soil moisture was also measured gravimetrically. Soil samples were collected from 0–1, 0–3, and 3–6 cm depth intervals at each site, oven dried, and gravimetric moisture calculations made. Fixed volume samples were collected from 0 to 3 and from 3 to 6 cm in a cylindrical sampler with a 5.4 cm

⁵ Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the products listed by USDA.

Table 4

Land use distribution for the regional sampling sites within each grid box

Ease grid number and location	Row crop	Pasture	Forest	Total sites
1 (Northwest)	4	1	4	9
2 (Northeast)	3	2	2	7
3 (West-central)	5	1	2	8
4 (East-central)	8	2	3	13
5 (Southwest)	3	1	2	6
6 (Southeast)	3	1	2	6
Total number	26	8	15	49
Fraction of total sites (%)	53	16	31	100

diameter in order to calculate bulk density for each sample. The volumetric moisture content for each soil sample was then calculated using the bulk density and the gravimetric moisture. An estimated bulk density of 1.5 g cm^{-3} was assumed to convert the 0–1 cm sample. Average volumetric moisture was calculated from the 0–3 and the 3–6 cm sample data for comparison to the measurement obtained from the Theta probe. This comparison was used to assess the accuracy of the factory provided relationship between dielectric constant and volumetric moisture for the probe.

Surface and sub-surface (1, 5, and 10 cm) soil temperature readings were collected at each site. The surface temperatures were measured using infrared thermometers (IRTs) (Omega Engineering Inc., OS643). The sub-surface soil temperatures were measured using digital thermometers (Omega Engineering Inc., TPD32). GPS coordinates, site photographs, 0–6 cm soil texture samples, and 0–2 cm soil samples for pesticide analysis were collected at each site. The GPS measurements were collected on the first day of sampling. Photographs of the site were taken the first and the last day of sampling.

The sampling sites at each location were located a minimum of 100 m from any field boundary. Three points were sampled within each row crop field; within the plant row, at 1/4 of the way between the rows, and at 1/2 of the way between the rows. For pasture and woodland sites a representative location was selected for the three sample points that were arranged in a triangle with each point approximately 10 m apart. Three Theta probe measurements were collected at each site (within the row, 1/4 row, and 1/2

row). Any organic residue was scraped from the surface prior to sampling. The three gravimetric samples (0–1, 0–3, and 3–6 cm) were collected at the 1/4 row location only, within 25 cm of the point where the Theta probe measurement was made. A rectangular shaped scoop was used to collect the 0–1 cm sample, while a cylindrical coring tool (Soilmoisture Equipment Corp., 200-A) was used for the fixed volume 0–3 and 3–6 cm samples. All samples were stored in soil moisture cans, the can numbers recorded, and the sample placed in coolers for transport. The gravimetric samples were weighed as soon as field sampling was completed and placed in ovens for drying. Samples were dried for 24 h at 105°C . The surface and subsurface (1, 5, and 10 cm) soil temperatures were also measured at the 1/4 row position only.

2.4. In situ measurements

Prior to the beginning of the study, Stevens-Vitel Hydra probes (Stevens Water Monitoring Systems, Inc.) were installed at 19 rain gage sites centered at three different depths (5, 20, and 30 cm) (Table 3). The measurement area of each sensor is a cylinder approximately 6 cm long with a 3 cm diameter centered on the central probe of the device. Like the Theta probes, the Hydra probes measure the dielectric properties of the soil and calculate volumetric soil moisture based upon these. The continuous soil moisture measurements from the in situ Hydra probes provided another spatial estimate of soil moisture over the study region for comparison to the measurements collected at the regional sites and the remotely sensed estimates. Data from prior research indicate good agreement between the Hydra probe estimates and observed volumetric soil water (Bosch, 2004). Measurements at the sites were taken every half hour at each site. The in situ network will provide continuous measurements of soil moisture for comparison to the collected satellite data, not only from AMSR-E but from future missions such as SMOS and Hydros as well.

2.5. Spatial correlation

Semi-variograms were employed to examine the spatial dependence of the soil moisture. For efficient

sampling design and statistical analyses, knowledge of the spatial autocorrelation and structure of the soil moisture are essential. In geostatistics, the semi-variograms are most widely used to quantify spatial correlation. The basic assumption of the semi-variograms is that measurements collected spatially closer to one another are more similar than those farther apart. It is also assumed that the semi-variogram depends solely upon separation distance but not location. The semi-variogram γ is defined (Journel and Huijbregts, 1978; Sposito, 1998) as:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^n \{Z(x_i) - Z(x_i + h)\}^2 \quad (1)$$

where n is the number of pairs of sample points, h is the separation distance or lag, $Z(x_i)$ and $Z(x_i + h)$ are the measured values at location x_i and $x_i + h$, respectively.

As the separation distance between the pairs of sample points increases, the semi-variogram γ generally increases until it levels off to the relatively constant value denoted by the sill, $\gamma(\infty)$, if the variables are stationary or homogeneous. Beyond the distance of the sill, the variation of the variables is no longer spatially autocorrelated.

2.6. In situ network validation

The reliability of the in situ network for providing long term data for evaluating the satellite measurements was examined using the time stability analysis and statistical techniques. The time stability concept was introduced by Vachaud et al. (1985) to characterize time-invariant association between spatial location and statistical parametric values of a given soil property. The technique has the potential to improve sampling scheme efficiency used to validate remotely sensed soil moisture measurements. The concept can be used to minimize the number of observation points without loss of information if a constancy of spatial soil moisture patterns is found. If areas maintain time stable characteristics, then a few stable sampling sites will represent mean soil moisture dynamics of given areas (Grayson and Western, 1998). It is also a useful tool for evaluating the representativeness of individual sites (Cosh et al., 2004; Jackson et al., 2004).

In order to analyze the time stability of a soil moisture field, two statistical metrics, the mean relative difference and the root mean square error of mean relative difference, are determined. The mean relative difference ($\bar{\delta}_{i,j}$) (Vachaud et al., 1985; Mohanty and Skaggs, 2001) is defined as:

$$\bar{\delta}_{i,j} = \frac{1}{n_t} \sum_{t=1}^{n_t} \frac{\theta_{i,j,t} - \bar{\theta}_{j,t}}{\bar{\theta}_{j,t}} \quad (2)$$

$$\bar{\theta}_{j,t} = \frac{1}{n_{j,t}} \sum_{i=1}^{n_{j,t}} \theta_{i,j,t} \quad (3)$$

$$\sigma(\delta)_{i,j}^2 = \frac{1}{n_t - 1} \sum_{t=1}^{n_t} - \left(\frac{\theta_{i,j,t} - \bar{\theta}_{j,t}}{\bar{\theta}_{j,t}} \bar{\delta}_{i,j} \right)^2 \quad (4)$$

where t is the number of dates, j is the number of fields, i is the number of sample points within field j at time t , $\bar{\theta}_{i,j,t}$ is a volumetric soil moisture at location i in field j and time t , $\bar{\theta}_{j,t}$ is the field mean soil moisture in field j , and time t , $\bar{\delta}_{i,j}$ is the mean relative difference of each sampling point, and $\sigma(\delta)^2$ is the variance of the relative difference.

The mean relative difference indicates whether the soil moisture measurement of a particular sample point is greater or less than the average soil moisture of the field. The mean relative difference plot, drawn by rank with error boundaries of standard deviation of the relative difference, determines which sample points illustrate the greatest time stability.

A site's bias and precision are given by the mean and variance of the relative difference, respectively. The root mean square error (RMSE) of mean relative difference, which combines bias and precision metrics (Jacobs et al., 2004), is defined as:

$$\text{RMSE}_{i,j} = \left(\bar{\delta}_{i,j}^2 + \sigma(\delta)_{i,j}^2 \right)^{1/2} \quad (5)$$

This combination statistic identifies time stable locations in watershed as those having low RMSE values.

2.7. Analytical methods

In order to examine trends over the observation period, averages were calculated which included all of the observed data at each site where data were

collected on that day. These averages in general included all 49 regional sampling sites. In some cases, due to instrument failure or sample loss, data were not collected. This occurred for only three out of 490 samplings (<1%). To examine variability, standard deviations were also determined.

The gravimetric moisture contents for the 0–3 cm and the 3–6 cm depth intervals were converted to volumetric moisture content for each daily measurement using the bulk density calculated for the fixed volume sample on that day. Because of difficulty collecting precise sample volumes, there was considerable variability in the bulk density values obtained. Outliers in the bulk density data were removed using the Grubbs' test for detecting outliers (Grubbs, 1969):

$$Z = \frac{|\text{mean} - \text{value}|}{\text{SD}} \quad (6)$$

where Z is the test statistic, M is the mean of the values, V is the value being tested, and SD is the standard deviation of the values. Bulk density samples at each site and each depth interval were collected every day for the 10 days of the study. Based upon an outlier probability level of 5%, the outlier test statistic was set at 2.29 (Grubbs, 1969). Bulk density values which yielded test statistics larger than or equal to 2.29 were removed from the data set. When values were removed the mean of the remaining values was used as an estimate of the bulk density for that day and that depth interval.

3. Results and discussion

3.1. Climate data

From June 1st through June 22nd, an average of 134 mm of precipitation fell over the study area. This produced fairly wet conditions at the beginning of the regional sampling. No precipitation occurred from June 23rd through the 28th (Fig. 2). This period was followed by several small rainfall events from June 29th through July 2nd (Fig. 2) that yielded an average of 54 mm. Actual precipitation varied from site to site. Two of the row crop sites received irrigation during the period from June 23rd through the 28th. Measurable precipitation was observed at several of

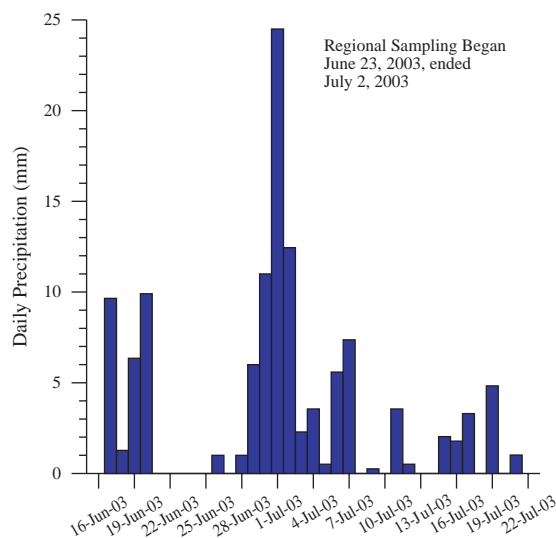


Fig. 2. Area weighted precipitation for the coverage area from June 17, 2003 to July 21, 2003.

the regional sites on June 29, June 30, and July 1. The precipitation was highly variable over the study area (Fig. 3). On the 29th, the greatest precipitation was observed in the Northeast, the West-central, and the Southeast grid cells. The precipitation received on June 30th and July 1st was more evenly distributed, with pockets of higher precipitation (Fig. 3). The greatest precipitation was observed on July 1, with up to 70 mm of precipitation falling in the southern portion of the study area as a result of the remnants of tropical storm Bill.

3.2. Soil moisture

Volumetric soil moistures were calculated for each soil sample. The volumetric soil moistures from the 0–1, 0–3, and 3–6 cm depth intervals at the 49 regional sites were then averaged across all the sites to examine the general trends. A drying trend was observed over the first 7 days of the regional sampling (Fig. 4). This was followed by a steady increase in soil moisture beginning on June 29th corresponding to the precipitation observed on that day. The greatest average soil moisture observed during the field campaign was on the last day, July 2nd (Fig. 4).

During drying conditions, the lowest values of soil moisture were observed in the surface 0–1 cm layer

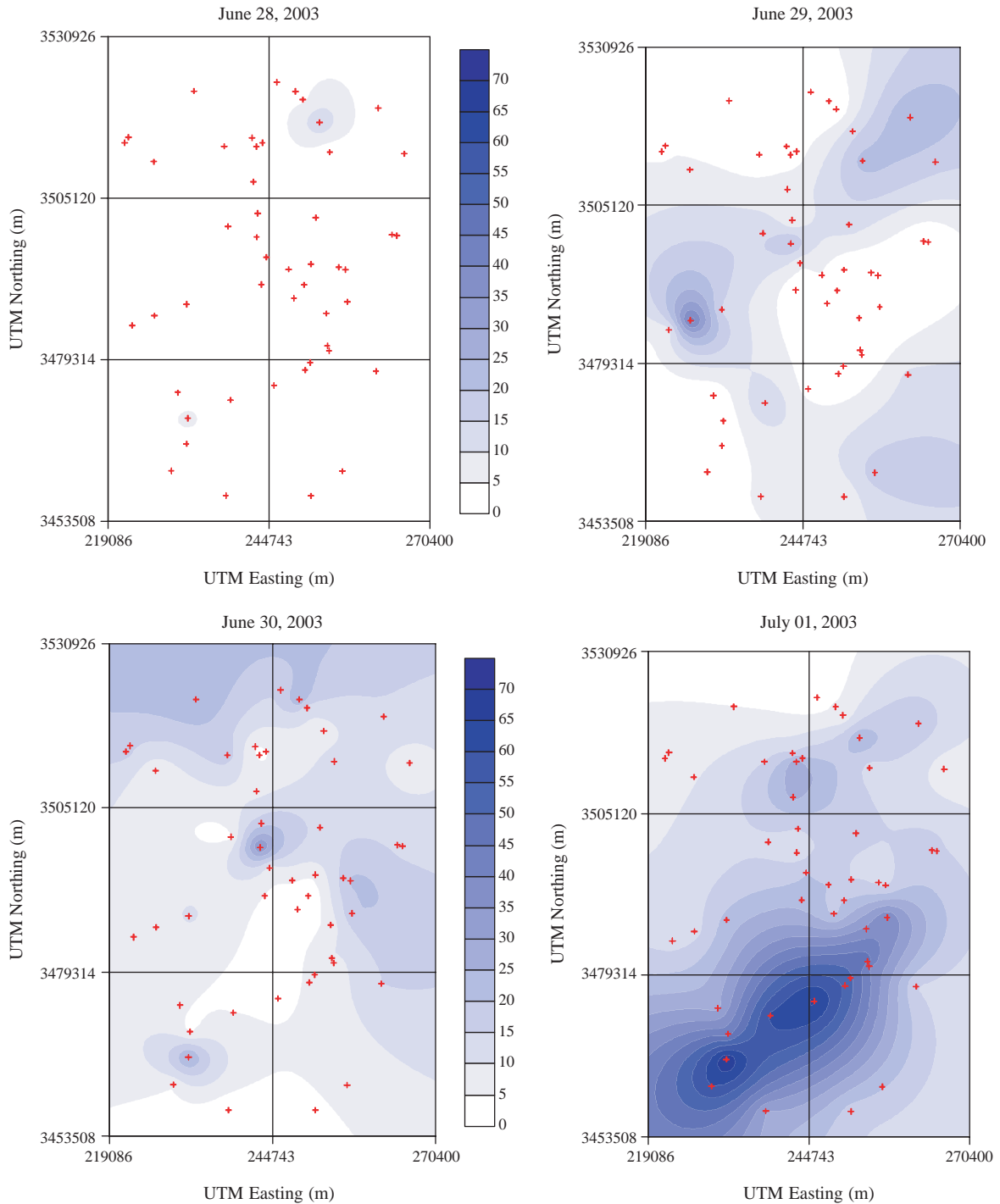


Fig. 3. Precipitation (mm) patterns observed over the study area from June 28 to July 1, 2003 (symbols indicate sampling points), interpolation between data points through Kriging.

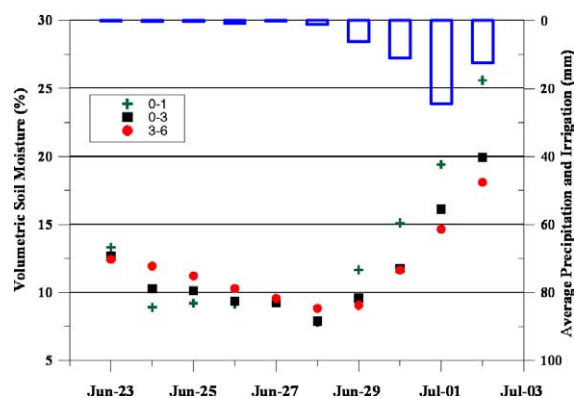


Fig. 4. Average volumetric soil moistures calculated from the assumed and calculated bulk densities and the gravimetric soil samples for the 0–1, 0–3, and the 3–6 cm depths, along with average precipitation and irrigation for the study area.

while the largest values were generally observed in the 3–6 cm layer. Following precipitation the reverse was generally observed, depending upon the precipitation volume received and the depth of infiltration. The greatest variability was observed in the 0–1 cm soil moisture, with standard deviations as high as 13% (Table 5). The least variability was observed in the 3–6 cm soil moisture, with typical standard deviations around 6. As has been observed by other researchers (Warrick and Nielsen, 1980) the relative spatial variability was greater when the soil was dry than when it was wet.

Similarly, the average and standard deviation of the Theta probe readings from the 0–6 cm depth intervals were also calculated (Table 5). A comparison was made between the soil moisture values

measured with the Theta probes and the soil moistures calculated from the gravimetric samples (Fig. 5). For the gravimetric samples, an average value was calculated using the 0–3 and the 3–6 cm sample values. In general, good agreement was observed between the two. Measurements obtained from the Theta probes were approximately 6.6% less than those obtained from the measurements calculated from the gravimetric samples. While considerable variance was observed between the two, this may be due to difficulties in obtaining accurate bulk density estimates. Small variations in the volume of the sample collected for these estimates can lead to large variations in the bulk density when fairly small samples are involved. In addition, the samples were collected at different specific locations typically separated by 25 cm. Some difference can be expected over even small distances due to local variations in soil type and micro-topography.

3.3. Soil textures

Soil samples were collected from the 0–6 cm depth interval at each of the 52 sampling sites and analyzed for texture (Table 2). As with most upland soils in the region, the soils contain a high percentage of sand and fairly low clay fractions. Based upon their characteristics, the majority of the surface textures sampled would be classified as loamy sands. The dominant soil types for the upland areas in this region are loamy sands and sandy loams. The textural characteristics were highly variable across the sites, with no apparent regional trends.

Table 5
Average and standard deviation (in parenthesis) of the observed data

Date	Rainfall/irrigation (mm)	0–1 cm Volumetric moisture from soil sample (%)	0–6 cm Volumetric moisture from soil sample (%)	Volumetric moisture from Theta probe (%)
23-Jun-03	0.1 (0.7)	13.3 (12.6)	12.6 (7.4)	11.6 (6.9)
24-Jun-03	0.2 (1.3)	8.9 (8.4)	11.1 (7.1)	10.5 (7.2)
25-Jun-03	0.2 (1.3)	9.2 (10.6)	10.7 (7.9)	9.4 (7.4)
26-Jun-03	0.9 (3.5)	9.2 (11.7)	9.8 (8.1)	8.6 (7.5)
27-Jun-03	0.2 (0.9)	9.5 (12.2)	9.4 (7.9)	8.7 (7.6)
28-Jun-03	1.2 (2.5)	7.8 (8.5)	8.5 (7.5)	8.0 (6.8)
29-Jun-03	6.2 (8.9)	11.7 (10.9)	9.3 (6.8)	8.9 (6.3)
30-Jun-03	11.0 (7.7)	15.1 (10.2)	11.7 (6.8)	12.2 (6.9)
1-Jul-03	24.5 (17.5)	19.4 (7.5)	15.4 (6.0)	16.1 (5.8)
2-Jul-03	No data	25.6 (10.7)	19.0 (6.1)	20.2 (5.8)

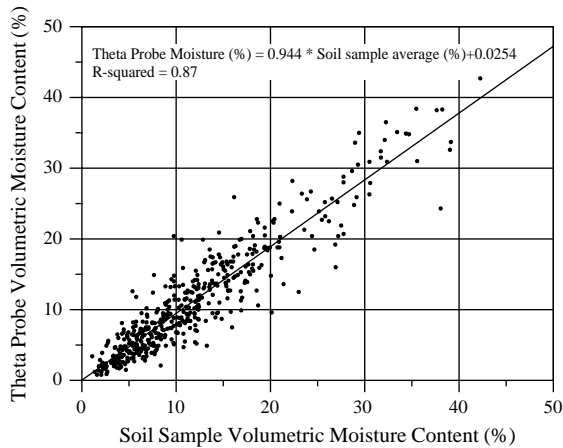


Fig. 5. Relationship between the volumetric moisture content measured with the Theta probes and the average volumetric moisture content for the 0–3 and the 3–6 cm gravimetric soil samples.

3.4. Soil temperature

The spatially averaged surface soil temperature data collected with the IRTs and the temperature probes were examined for trends (Fig. 6). The surface temperatures at the start of the field campaign averaged 34 °C. During the period from June 23rd to June 27th the average surface temperatures increased to 36 °C. From June 28th through July 2nd surface soil temperatures fell to 27 °C following the beginning of the precipitation due to enhanced evaporation as a consequence of increased soil moisture. Similar patterns were observed in the soil temperatures

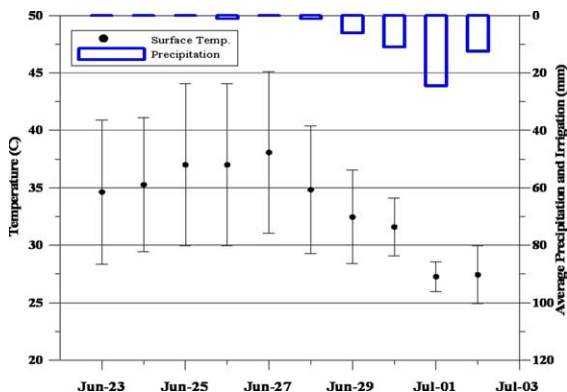


Fig. 6. Mean and standard deviation of the surface soil temperatures for the 49 regional sampling sites measured over the field campaign.

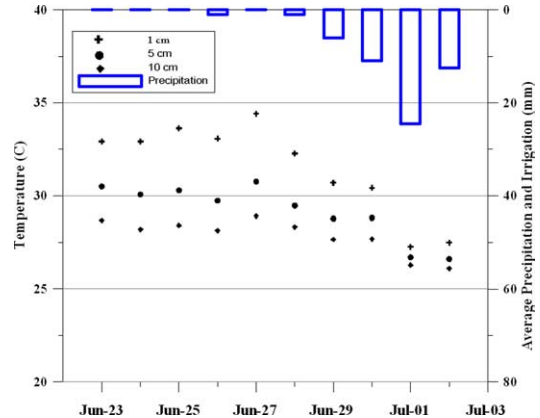


Fig. 7. Average soil temperatures at three depths for the 49 regional sampling sites measured throughout the field campaign.

(Fig. 7). Soil temperatures were approximately 5 °C cooler at the 10 cm depth measurement than they were at the 1 cm depth measurement on June 23rd, but they were approximately equal on July 2nd following the periods of rain.

3.5. Impact of land use

The primary land covers that were sampled were forest (15 sites), cotton (14 sites), peanuts (10 sites), and pasture (eight sites). Theta probe soil moisture measurements were separated out by land use to examine differences due to vegetation cover (Fig. 8). Soil moisture in the tilled cotton and peanut fields were very similar. Moisture contents in the pasture

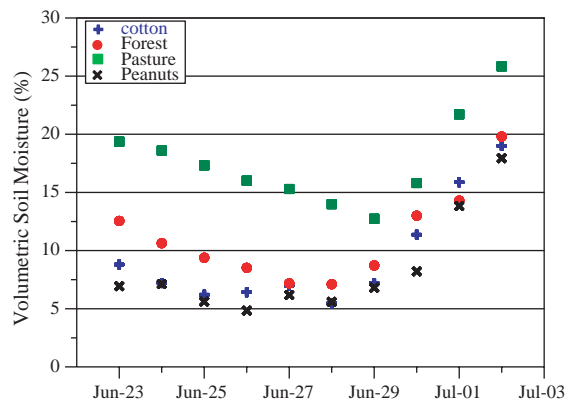


Fig. 8. Average soil moisture content from the Theta probe in each of the major land use categories.

fields were considerably higher than the other covers. However, this was biased by two pasture sites, GA06 and GA24, which were consistently very wet. The soil moistures at these two sites were greater than 30% every day throughout the study. Both of these sites were at lower elevations bordering wetland areas. The forested sites were consistently wetter than the row crop sites, but not as wet as the pasture sites. Typically, the sandier less productive soils are used for forest production. However, examination of the particle size data for these sites indicates that in general the sand fraction of these sites was consistent with that observed throughout the other sites (Table 2). Fifteen of the row crop sites contained irrigation systems. Of these 15, two received irrigation on June 26th, 15 mm at site 26 and 18 mm at 28. This raised the soil moisture average slightly on the 27th (Fig. 8).

3.6. Spatial correlation

Data from June 23, 2003 through July 2, 2003 were extracted from continuous in situ measurements matched to the time of the Aqua overpass (1:30 p.m. EST) and the regional sampling (11:30 a.m. to 2:30 p.m. EST). Spatial structure of the in situ network showed the correlation lengths varied between 1821 and 8098 m over the study period (Table 6). Based upon this structure, all the variability of soil moisture can be obtained by sampling at an 8000 m length scale. As the minimum spacing between in situ sites in

the network is approximately 5320 m, relatively few sites were found to be spatially dependent.

Also using geostatistical methods, daily maps of soil moisture were developed using the field site average Theta probe data (Fig. 9). Local measurements were used to generate contour images of soil moisture throughout the region using a kriging based interpolation procedure. As seen with the averaged data (Fig. 4) drying was observed from June 25th to June 29th and wetting from June 29th through July 2nd. As anticipated, the change in moisture content reflected the precipitation received (Fig. 3). On June 30 an increase in soil moisture was observed across the West-central to the northeast section of the study area (Fig. 9), which was related to the precipitation that fell there (Fig. 3). Similarly, a widespread increase in moisture content was observed across the southern portion of the study area on July 2, which was related to the rain received there on July 1 (Fig. 9).

Jackson et al. (2005) present the results of the analysis of the data collected using the PSR instrument. PSR data were collected on June 25th, 29th, and the 30th. The PSR measures surface brightness temperatures. Higher brightness temperatures indicate lower soil moisture while lower temperatures indicate greater soil moisture (Jackson et al., 2005). The PSR data indicated a decrease in brightness temperatures between June 25th and June 29th, with greater changes observed across the northern and the southern grid boxes. The PSR data showed a larger and more extensive decrease in brightness temperatures on June 29th. In general, similar trends were observed in the regional soil moisture maps from the theta probe data (Fig. 9).

Table 6
Semivariograms for the in situ network soil moisture data

Date	Sill $r(\infty)$	Distance (m)	Correlated pairs of the 289 total pairs	Dependence % of networks
6/23/2003	15.96	4062	18	6.23
6/24/2003	1.39	4179	18	6.23
6/25/2003	12.35	4379	20	6.92
6/26/2003	11.13	4820	30	10.38
6/27/2003	1.08	7573	64	22.15
6/28/2003	10.26	8098	76	26.30
6/29/2003	1.25	7983	74	25.61
6/30/2003	0.32	1821	0	0.00
7/1/2003	3.86	7464	62	21.45
7/2/2003	2.60	3122	10	3.46

3.7. In situ network validation

In order to examine the applicability of the in situ network for representing regional soil moisture conditions over the sample area, the mean relative difference (Eq. (2)) was calculated using the average soil moisture contents of the entire region from the Theta probe measurements (i.e. the 50 km by 75 km area) and the 5 cm Hydra in situ point observations (Fig. 10). Negative mean relative differences indicate the sites have drier spatial patterns than the regional mean while positive mean relative differences

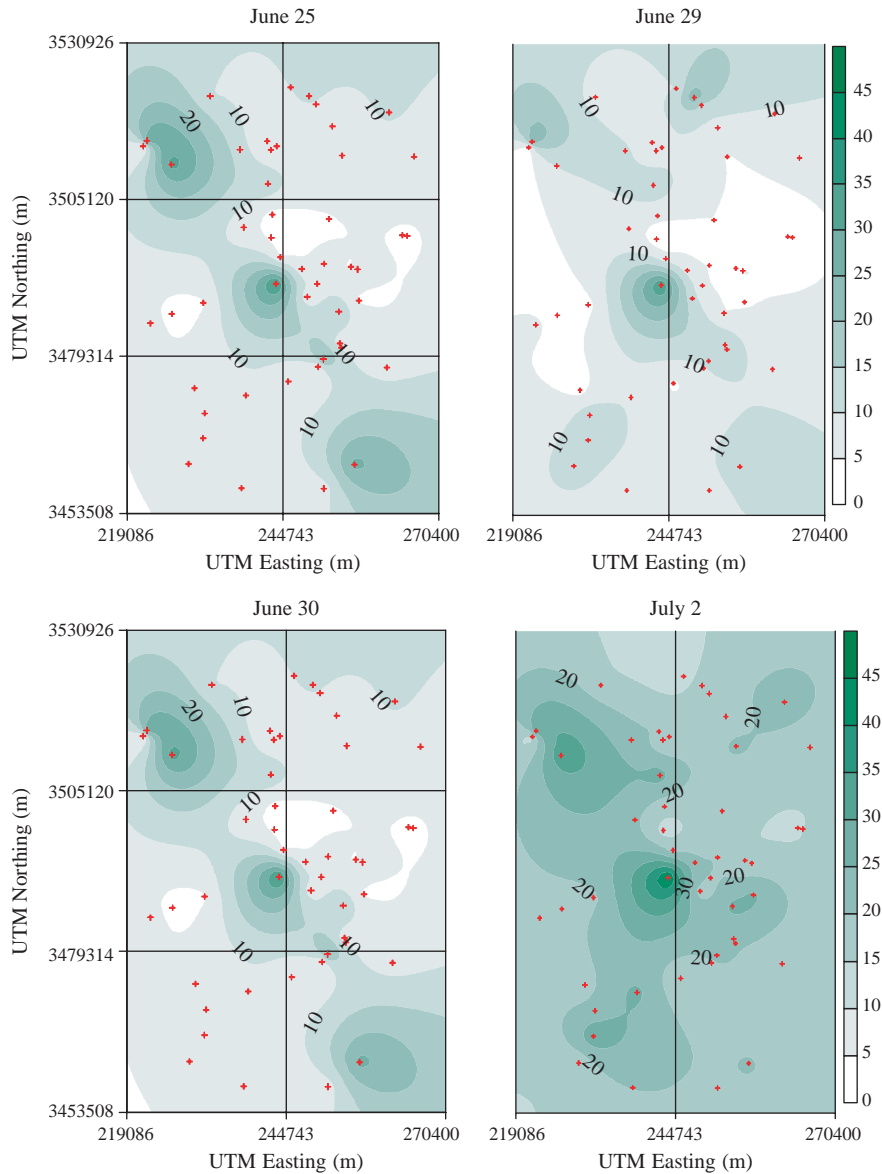


Fig. 9. Moisture content determined through kriging interpolation of the average Theta probe readings (%) (symbols indicate sampling points) collected during the regional sampling.

indicate the sites have wetter spatial patterns than the regional mean. The standard deviation of mean relative difference and RMSE values are also indicators of which sites consistently overestimate or underestimate the mean (Fig. 10).

Sampling location RG66, the most stable station with a mean relative difference and RMSE near zero,

represented the regional mean within $\pm 1\%$ volumetric soil moisture (Fig. 10). Thirteen stations were drier than the regional mean soil moisture content. Drier stations had better time stability, with lower standard deviations and RMSEs than the wetter stations. This was partially due to extremely high soil moisture observed at RG26. Based on this

Table 7

Matched pair *t*-test *p*-values for the in situ soil moisture network with 17 hydra probe stations compared to the theta probe measurements for the entire region within each of the 6 Ease-GRIDs

Case	Regional	Ease grid 1	Ease grid 2	Ease grid 3	Ease grid 4	Ease grid 5	Ease grid 6
1	0.0128(*)	0.0000(***)	0.1351	0.0594	0.0031(**)	0.6139	0.0052(**)
2					0.0015(**)	0.3069	
3	0.0064(*)	0.0000(***)	0.0675	0.0297(*)			0.0026(**)

(Case 1) $H_0: \mu_{\text{Hydra}} = \mu_{\text{Theta}}$; (Case 2) $H_0: \mu_{\text{Hydra}} < \mu_{\text{Theta}}$ (Case 3) $H_0: \mu_{\text{net}} > \mu_{\text{Theta}}$. *, **, ***: significant at the 0.05, 0.01, 0.001 probability levels.

analysis and site characterization, we eliminated the soil moisture values from RG26 as an outlier and RG65 for missing values from the remaining time stability analyses.

The soil moisture measured using 5 cm depth in situ Hydra probes were obtained for each half hour reading and averaged across all nineteen sites. Comparisons were made among the in situ, the Theta probe, and the gravimetric estimates of soil moisture. Based upon the results of the time stability analysis, data from RG26 was not used for this analysis. The regional data represent the average readings collected at the 49 regional sites with the Theta probe. The Theta probe data represented a broader coverage area (Fig. 1). In general, good agreement was observed between the Theta probe data and the in situ Hydra data (Fig. 11). The soil moisture measured from the in situ probes were slightly lower (around 2%) than that observed with the Theta probe. The in situ probes appear to do a reasonable job of representing average surface soil

water conditions over the sample area and more closely reflect the temporal nature of the soil moisture.

To identify the ability of in situ soil moisture stations to characterize the average soil moisture within each of the six EASE-Grid cells, the time stability was conducted separately for each cell. A cell's average soil moisture content was determined by averaging the Theta probe measurements made in that EASE-Grid. Fig. 12 shows that the most stable stations represented the EASE-Grid mean soil moistures within $\pm 3\%$ except within EASE-Grid 1. The most stable station in EASE-Grid 1 was on average drier than the EASE-Grid mean soil moisture by 12.1%. For Ease-Grids 1, 2, 3, and 6, 10 or more stations were drier than the grid mean. Matched pair *t*-tests show that while the mean soil moisture content of the entire network was drier than the regional mean, EASE-Grids 2, 3, and 5 were well characterized by the in situ network (Table 7).

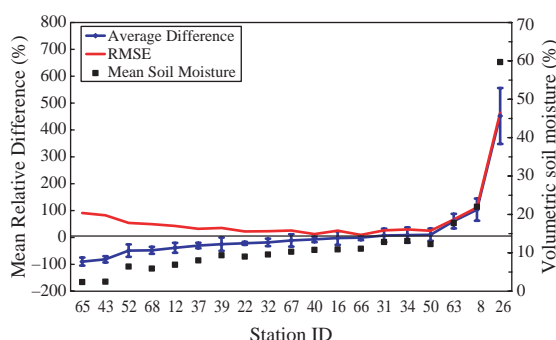


Fig. 10. Rank ordered mean relative difference with standard deviation error bars, root mean square error, and mean soil moisture content (%) for the in situ soil moisture nineteen stations.

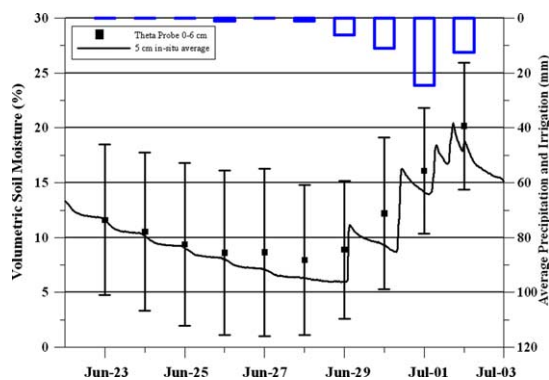


Fig. 11. Average soil moisture calculated from the Theta probe readings (error bars are one standard deviation above and below the average) and from the in situ Hydra probes plotted with average daily precipitation.

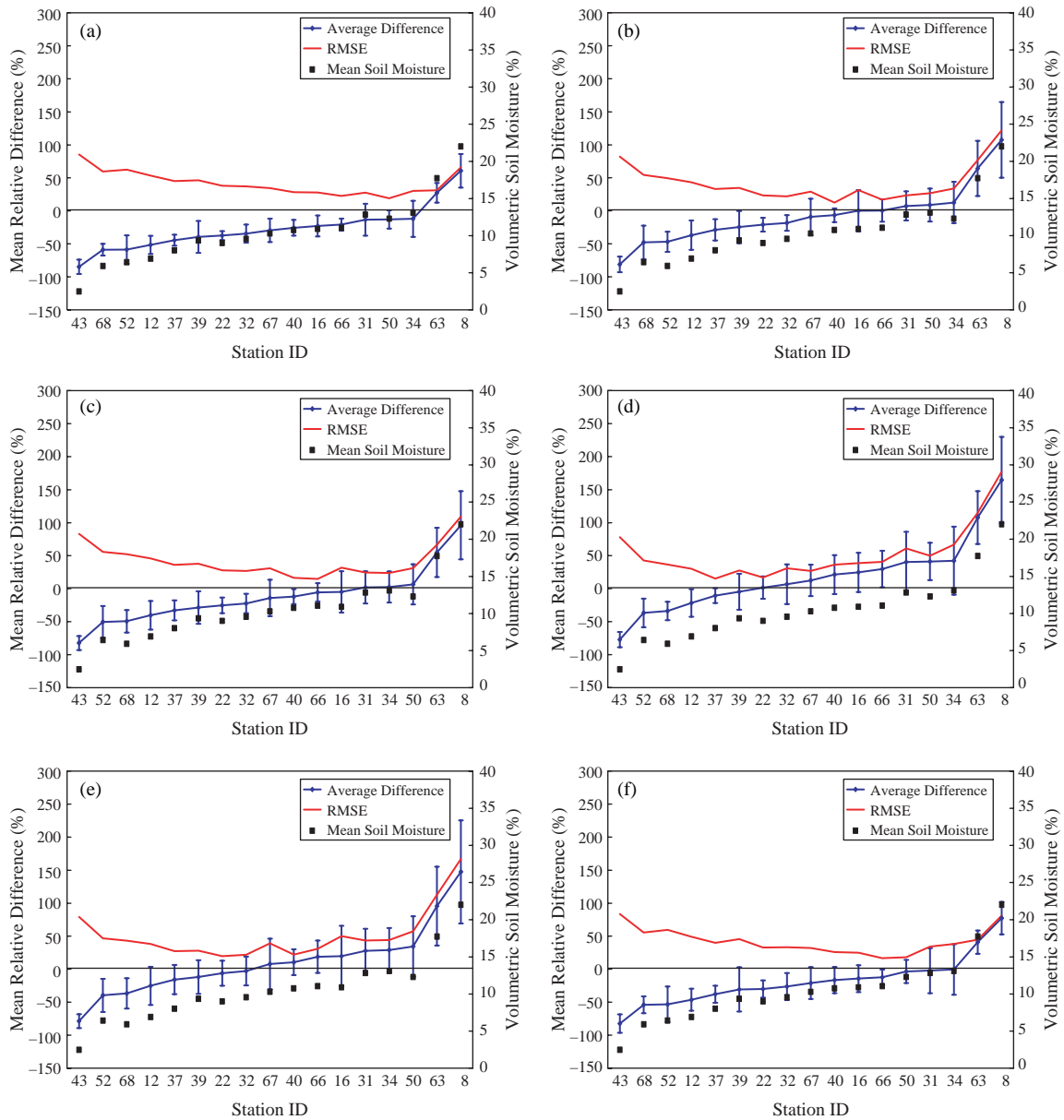


Fig. 12. Rank ordered mean relative difference with standard deviation error bars, root mean square error, and mean soil moisture content (%) for the in situ soil moisture 17 stations within six EASE-Grids (a) EASE-Grid 1 ~ (f) EASE-Grid 6.

4. Conclusions

The climate, soil moisture, and soil temperature observations described here represent the core data collected during the GA component of the SMEX03 remote sensing project. The data provide a valuable

resource for validation of the soil moisture estimates derived from the AMSR and the PSR sensor readings as well as other data platforms, which remotely sense soil moisture and soil temperature.

While considerable variability was observed in the soil moisture data, obvious drying and wetting trends

were visible in the data corresponding to periods of precipitation. The composite soil moisture obtained by averaging the 49 regional sampling points appears to yield a good estimate of the regional soil moisture during both wet and dry periods. This composite value represents the geographic and vegetative diversity observed across the study region.

A comparison between the Theta probe soil moistures and the soil moistures derived through soil sampling indicates that for this region, the Theta probe appears to yield a good estimate of soil moisture (Fig. 5). Because of the errors introduced in gravimetric sampling due to sample loss and inaccurate estimates of bulk density, it appears that the Theta probe measurements present a superior alternative to gravimetric sampling. In addition, because the method is considerably simpler, it may be possible to increase sample numbers thus improving the estimates of the composite soil moisture obtained.

Soil moisture differences were observed by land use category. The pasture sites were the wettest, followed by the forest. The row crop sites were the driest. A more detailed analysis may be necessary to evaluate if these differences are due to topography, soil texture, surface residue, or land management. However, it does appear that a proportion of each of these vegetation types is necessary to yield an accurate composite value.

The in situ network of Hydra probes appears to have a somewhat wet bias of regional soil moisture conditions. While time stability analysis found a fairly equal distribution of the degree of wetness observed at the sites. The analysis also indicated that RG26 is considerably wetter than the other sites and appears to be the cause of the wet bias. Removal of this site resulted in the network underestimating the regional data. Overall, these results indicate that the in situ network will be a good resource for long-term calibration of remotely sensed soil moisture evolution. Additionally, the network yields soil moisture readings at a much higher temporal data resolution than can be obtained through field campaigns such as that described here. Time stability analysis of the in situ data collected across the studied EASE-grid cells indicate the in situ data represent mean conditions well within three of the six cells but that

additional in situ sites may be required to obtain better mean estimates within the remaining three cells.

Acknowledgements

This effort involved many State, Federal, and Private agencies. We would like to thank the Soil Moisture Experiment 2003 Science Team, the staff of the Southeast Watershed Research Lab, Scientists from the NASA Goddard Space Flight Center, Scientists from the USDA National Peanut Lab, and Scientists from the USDA-ARS National Soil Tilth Lab for their critical roles in the study. We would like to thank the many graduate students from the University of South Carolina, the University of Georgia, the University of Florida, and the North Carolina State University for their able assistance in the field sampling. We also acknowledge the National Aeronautics and Space Administration for their generous contributions to the study. This work was supported by the NASA Aqua AMSR, Terrestrial Hydrology, Global Water Cycle Programs, and NIP Grant NAG5-10567.

References

- Armatys, M., Masters, D., Komjathy, A., Axelrad, P., Garrison, J., 2000. Exploiting GPS as a new oceanographic remote sensing tool. *Proc. Institute of Navigation Technical Meeting*, 26–28 2000. 26–28 January.
- Brodzik, M.J., Knowles, K., 2002. EASE-Grid: a versatile set of equal-area projections and grids. Goodchild, M., Kimerling, A.J. *Discrete Global Grids*. National Center for Geographic Information & Analysis, Santa Barbara, CA, USA. (Accessed 8/07/04) http://www.ncgia.ucsb.edu/globalgrids-book/ease_grid.
- Bosch, D.D., 2004. Comparison of capacitance-based soil water probes for Coastal Plain Soils. *Vadose Zone J.* 3(2004): 1380–1389.
- Bosch, D.D., Sheridan, J.M., Davis, F.M., 1999. Rainfall characteristics and spatial correlation for the Georgia coastal plain. *Trans. Am. Soc. Agr. Eng.* 42 (6), 1637–1644.
- Cosh, M.H., Jackson, T.J., J., T., Bindlish, R., Prueger, J.H., 2004. Watershed scale temporal persistence of soil moisture and its role in validation satellite estimates. *Remote Sensing of Environment* 92, 427–435.
- Gaskin, G.J., Miller, J.D., 1996. Miller, Measurement of soil water content using a simplified impedance measuring technique. *J. Agric. Res.* 63, 153–160.

- Grayson, R.B., Western, A.W., 1998. Towards aerial estimation of soil water content from point measurements: Time and space stability of mean response. *J. Hydrol.* 207, 68–82.
- Grubbs, F., 1969. Procedures for detecting outlying observations in samples. *Technometrics* 11 (1), 1–21.
- Hubbard, R.K., Berdanier, C.R., Perkins, H.F., Leonard, R.A., 1985. Characteristics of selected upland soils of the Georgia coastal plain. USDA. Ag. Res. Service, 72. ARS-37.
- Koster, R.D., Suarez, M.J., Heiser, M., 1999. Variance and predictability of precipitation at seasonal-to-interannual time scales. *J. Hydrometeorology* 1 (1), 26–46.
- Jackson, T.J., Bindlish, R., Gasiewski, A.J., Stankov, B., Klein, M., Njoku, E.G., Bosch, D., Coleman, T., Laymon, C., Starks, P., 2005. Polarimetric scanning radiometer C and X band microwave observations during SMEX03. *Trans. Geosci. Remote Sens.* In Press.
- Jackson, T.J., O'Neill, P., 1990. Attenuation of soil microwave emission by corn and soybeans at 1.4 and 5 GHz. *IEEE Trans. Geosci. Remote Sens.* 28, 978–980.
- Jackson, T.J., O'Neill, P., 1987. Temporal observations of surface soil moisture using a passive microwave sensor. *Remote Sens. Environ.* 21, 281–296.
- Jackson, T.J., Hurkmans, R., Hsu, A., Cosh, M.H., 2004. Soil moisture algorithm validation using data from the advanced microwave scanning radiometer (AMSR-E) in Mongolia. *Italian J. Remote Sens.* 30/31, 23–32.
- Jacobs, J.M., Mohanty, B.P., Hsu, E.C., Miller, D., 2004. SMEX02: Field scale variability, time stability and similarity of soil moisture. *Remote Sens. Environ.* 92 (4), 436–446.
- Journel, A.G., Huijbregts, C.J., 1978. *Mining Geostatistics*. Academic Press, New York.
- Laymon, C.A., W, L., Crosson, T.J., Jackson, A., Manu, A., Tsegaye, T.D., 2001. Ground-based passive microwave remote sensing observations of soil moisture at S-band and L-band with insight into measurement accuracy. *IEEE Trans. Geosci. Remote Sens.* 39, 1844–1858.
- Leese, J., Jackson, T., Pitman, A., Dirmeyer, P., 2001. GEWEX/BAHC international workshop on soil moisture monitoring, analysis and prediction for hydrometeorological and hydro-climatological applications. *Bulletin of the American Meteorological Soc.* 82, 1423–1430.
- Le Vine, D.M., Kao, M., Tanner, A.B., Swift, C.T., Griffis, A., 1990. Initial results in the development of a synthetic aperture microwave radiometer. *IEEE Trans. Geosci. Remote Sens.* 28, 614–619.
- Le Vine, D.M., Jackson, T.J., Swift, C.T., Haken, M., Bidwell, S.W., 1994. ESTAR measurements in the Southern Great Plains experiment (SGP99). *IEEE Trans. Geosci. Remote Sens.* 39, 1680–1685.
- Masters, D., Axelrad, P., Zavorotny, V., Katzberg, S.J., Emery, W., 2000. GPS signal scattering from land for moisture content determination. *Proc. IEEE IGARSS 2000*. Honolulu, HI, July 24–28.
- Masters, D., Axelrad, P., Zavorotny, V., Katzberg, S.J., Lalezari, F., 2001. A passive GPS bistatic radar altimeter for aircraft navigation. *Proc. ION GPS 2001*. Salt Lake City, 2001.
- Mohanty, B.P., Skaggs, T.H., 2001. Spatio-temporal evolution and time-stable characteristics of soil moisture within remote sensing footprints with varying soil, slope, and vegetation. *Advances in Water Resources* 24, 1051–1067.
- Piepmeyer, J.R., Gasiewski, A.J., 2001. Gasiewski, High-resolution passive microwave polarimetric mapping of ocean surface wind vector fields. *IEEE Trans. Geosci. Remote Sens.* 39, 606–622.
- Sheridan, J.M., 1997. Rainfall-streamflow relations for coastal plain watersheds. *Applied Eng. Agriculture* 13 (3), 333–344.
- Sposito, G., 1998. *Scale dependence and scale invariance*. Cambridge University Press, Cambridge, MA.
- Vauchaud, G., Passerat de Silans, A., Balabanis, P., Vauclin, M., 1985. Temporal stability of spatially measured soil water probability density function. *Soil Sci. Soc. Am. J.* 49, 822–828.
- Warrick, A.W., Nielsen, D.R., 1980. Spatial variability of soil physical properties in the field. In: Hillel, D. (Ed.), *Applications in Soil Physics*. Academic Press, New York, NY.